



The role of constructed wetlands in secondary effluent treatment and water reuse in subtropical and arid Australia

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Abstract

Water reclamation and reuse is being actively promoted in Australia. In Queensland, surface-flow constructed wetlands with a diversity of macrophyte types offer the greatest potential for effluent polishing. Constructed wetlands in subtropical climates in coastal regions and arid climates in inland western regions are conducive to high macrophyte growth rates and nutrient removal, in particular nitrogen, producing an effluent suitable for irrigation, restoration of wetlands and/or release into natural waterways. Faecal-coliform removal is also high, producing effluent with <1000 cfu/100 mL and as low as 100 cfu/100 mL, acceptable for agricultural irrigation. Constructed wetlands can be designed to maximise the removal of both nutrients and pathogens by enhancing macrophyte diversity and natural disinfection processes by incorporating lagoons, shallow-water wetlands and subsurface-flow wetlands into the treatment train. Surface-flow wetlands can also be designed to minimise mosquito breeding by increasing macro-invertebrate predators, thereby alleviating community concerns about potential health risks. This paper addresses the role of constructed wetlands in nutrient and pathogen removal in Queensland's wetlands, and presents three case studies with respect to effluent reuse.

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1. Introduction

Wastewater reclamation leading to water-reuse opportunities has gained considerable importance over the past decade, particularly in continents and countries where water is a scarce resource (Anderson et al., 2001; Asano, 1998; US EPA, 2004). Municipal wastewater

provides two essential resources—nutrients and water. Both are essential for plant growth. Agriculture, horticulture, forestry, golf courses, parks and gardens depend on these resources. In Australia, currently very little sewage effluent is reclaimed and reused. Typically, treated effluent is discharged into rivers, estuaries and oceans. Excessive nutrients may cause eutrophication and impact ecosystem health. At the same time, soil erosion and increased agriculture are removing nutrients from the soil, causing a depletion

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of fertility. Fertilisers can be added, but at a large economic cost. Water for irrigation, industrial use and human use is removed from rivers, lakes, reservoirs and aquifers at a large environmental cost. This depletion of water resources impacts on stream flows and natural aquatic ecosystems.

Now that water is recognised socially, economically, and politically as a critical resource requiring sustainable management, there needs to be a shift away from purifying water simply to be discharged directly back into rivers and oceans, unless it assists in restoring environmental flows. The cost of wastewater reclamation and the availability of water for reuse must be affordable to the community (Sala and Serra, 2004). The environmental impacts from the treatment processes must be minimal, safeguarding aquatic ecosystems, reducing energy usage, minimising greenhouse gas emissions and minimising unwanted/harmful by-products. Water recycling projects produce positive externalities (Sala and Serra, 2004).

Water reclamation and reuse can return nutrients and water to the land, restore stream flows and bring life back to aquatic ecosystems. However, a major issue and risk with sewage effluent reuse is the potential of sewage-borne pathogens. The direct release of reuse water for the irrigation of agriculture and horticultural crops or recreational areas is viewed as posing potential risks to human health (Bahri et al., 2001; Carr et al., 2004; Kracman et al., 2001).

Water disinfection by chlorination has eliminated most water-borne infectious diseases. However, current disinfection processes are costly and produce unwanted by-products. For example, the disinfection by-products, trihalomethanes, are carcinogenic (Boorman et al., 1999). Thus, we need innovative systems, designed to reclaim nutrients and water from wastewater for reuse, while also removing pathogens. Such systems must be environmentally sustainable, socially accepted and cost-effective: constructed wetlands are a prime candidate. However, the acceptability of constructed wetlands as an integral component of sustainable water management for wastewater reclamation and reuse relies upon their compliance with water-quality guidelines to minimise human and ecosystem health risks.

The performance efficiency of constructed wetlands to transform and recycle nutrients is well understood (IWA, 2000; US EPA, 2000). Constructed wet-

lands also provide suitable conditions for pathogen removal. Processes for bacterial removal include physical–chemical factors such as solar irradiation (UV light) and temperature (Zdragas et al., 2002), filtration (Arias et al., 2003), adsorption and subsequent sedimentation (Davies and Bavor, 2000) and biological factors such as predation and competition, attack by lytic bacteria and bacteriophages (viruses), natural death and decay. An approach to water reuse using constructed wetlands could eliminate disinfection by-products from treatment processes.

In Hawaii, a wetland reclamation facility was designed to treat sewage effluent from a waste-stabilisation pond. The reclamation facility included a wetland of water hyacinth ponds plus chemical flocculation, filtration and ultraviolet light disinfection, and produced a final effluent with <1 cfu/100 mL (faecal coliforms). Four other groups of sewage-borne pathogen indicators (enterococci, *C. perfringens*, F-specific coliphage, total heterotrophic bacteria) were also reduced, with coliphage being very low in the pond treatment (Fujioka et al., 1999). Thus, treatment trains comprising waste-stabilisation ponds, surface-flow wetlands with floating and emergent macrophytes and open-water sections could enhance natural disinfection processes.

2. Constructed wetlands in Australia

Constructed wetlands have emerged as a viable option for helping to solve a wide range of environmental and water-quality problems (IWA, 2000; US EPA, 2000). Wetland systems are particularly attractive alternatives where they can become an integral part of the overall landscape plan. Constructed-wetland technology is used extensively in North America and Europe. However, despite several pilot projects in Australia in the 1990s (Greenway and Simpson, 1996; Greenway and Woolley, 1999, 2001; QDNR, 2000), this wastewater-treatment technology has not widely been adopted in Australia. Interest in constructed wetlands for the treatment of municipal wastewater diminished in the late 1990s. This may have been because of relatively poor phosphorus removal (Greenway and Woolley, 1999; QDNR, 2000) and government pressure to upgrade and augment sewage treatment plants to produce a very high-quality tertiary effluent, or concern

that surface-flow constructed wetlands may be potential breeding sites for mosquitoes (NHMRC, 1999; QDNR, 2000). Greenway et al. (2003) have recently shown that predation of mosquito larvae by aquatic invertebrates controls the larvae and prevents the development of pupae. Thus, there is minimal health risk in terms of these wetlands being breeding grounds for mosquitoes, if designed and managed to maximise macro-invertebrate predators.

Constructed surface-flow wetlands also require more land area than a concrete tertiary Biological Nutrient Removal plant. However, these wetlands provide wildlife habitat, landscape enhancement and passive recreational benefits which are not afforded by concrete buildings. Thus, a resurgence in the application of constructed wetlands in Australia would provide multiple benefits for sustainable water management.

In South Australia, treated sewage effluent after pretreatment in constructed wetlands is stored in previously unused brackish aquifers for irrigation of parks during dry weather. Recycled water from the Bolivar Wastewater Treatment Plant is being trialled for irrigation of market gardens (Barnett et al., 2000). Again, wetlands can be used to improve water quality, with savings in water and infrastructure costs as well as providing economic, environmental and social benefits.

As we have seen in the preceding sections, community benefits include improved aesthetics, passive recreation, and even economic resources, but what are some of the community concerns? In Australia, there have been both government (regulatory and health) and community concerns about mosquito breeding in surface-flow wetlands, and the effectiveness of water-quality treatment in terms of nutrient and pathogen removal. For public acceptance of constructed wetlands as a component of the treatment for wastewater reuse, these issues need to be addressed.

3. Constructed wetlands and the mossie myth

While most mosquitoes are opportunistic breeders, they will only deposit eggs if a suitable body of water is available. In aquatic ecosystems, mosquito larvae are an integral component of aquatic food webs. Mokany and Shine (2002) found that female mosquitoes use both chemical and biological cues to assess the suitability of water bodies for breeding. The presence of exist-

ing larvae was a strong attractant to further egg laying, indicating that the habitat is suitable for larval development. Thus, a critical and significant issue for successful mosquito breeding is larval survival and whether adult mosquitoes emerge from pupae. It is the author's view that if constructed wetlands are designed to function as wetland ecosystems with a diversity of aquatic organisms, then it is likely that the predator-prey mix would control mosquito breeding.

Wetlands also support a diversity of aquatic animals including micro-crustaceans (copepods, ostracods and claderans), shrimps, crayfish, insects (dragonfly larvae, water beetles and water boatman), pond snails, tadpoles, frogs and fish. These organisms are a crucial component of wetland ecosystems, providing invaluable food-web linkages between plants, microorganisms and other animals. Predator-prey relationships are important in the control of mosquitoes (Greenway et al., 2003).

Wetland plant diversity is important for determining macro-invertebrate associations (De Szalay and Resh, 2000) and wildlife diversity (Knight et al., 2001) because of the creation of habitats and food resources. Wetzel (2001) noted that the most effective wetland ecosystems "are those that possess maximum biodiversity of higher aquatic plants and periphyton associated with the living and dead plant tissue".

Walton (2002) noted that in the arid south-western United States, constructed treatment wetlands can increase mosquito production if there is poor water quality and dense coverage of submerged dead vegetation. Greenway et al. (2003) found that dense stands of *Typha* with an accumulation of submerged dead stems and isolated pockets of water are suitable for mosquito breeding. Similarly, dense floating mats of *Paspalum* grass and *Persicaria* are also suitable for mosquito breeding, but of limited habitat value for many macro-invertebrates due to the lack of swimming space and low dissolved oxygen. Mosquito larvae are surface breathers and can survive in anaerobic conditions. However, many aquatic macro-invertebrate predators are also surface breathers (e.g. notonectid bugs and water beetles) or surface predators (e.g. pond skaters).

A study of four municipal-treatment wetlands (Greenway et al., 2003) found that the wetland with shallow marsh and deeper ponds had the greatest species richness of macrophytes (38 species) and

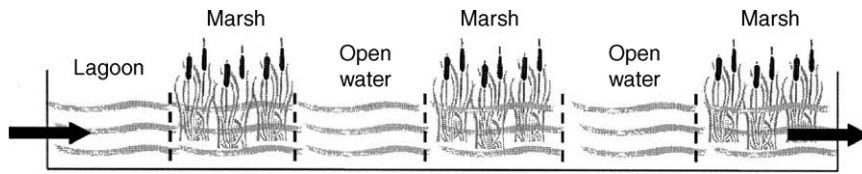


Fig. 1. Example of a surface-flow wetland in Queensland (Cooroy, Noosa Shire Council).

macro-invertebrates (90 taxa) and the lowest occurrence of mosquito larvae (<1% of dips). Wetlands dominated by dense monospecific stands of *Typha* had fewer macro-invertebrate taxa and a higher proportion of mosquito larvae. From our study, we concluded that a marsh with a diversity of macrophytes appears optimal for macro-invertebrate biodiversity and the control of mosquito larvae by predation. The effectiveness of *Gambusia* (mosquito fish) in the control of mosquito larvae in Australian wetlands and waterways has not been scientifically proven, with mosquitoes only making up a small part (<10%) of their diet. "Several authors have observed that *Gambusia* may actually encourage mosquito populations by preying on their invertebrate predators" (NSW NPWS, 2003). Fish will also consume frog tadpoles. The key to mosquito management is to ensure a well-balanced ecosystem supporting a diversity of aquatic organisms.

4. Constructed wetlands for effluent treatment in Queensland

Free-water surface-flow systems are common in Queensland and usually consist of several cells with sections of densely vegetated shallow marsh and open-water areas with duckweed or submerged plants and/or deeper lagoons (Fig. 1) (Greenway and Woolley, 1999; Greenway, 2003; Greenway et al., 2003). A large variety of wetland plant species has been used (Greenway, 2003).

Combined systems have also been used incorporating lagoons (waste-stabilisation ponds), surface-flow cells and subsurface-flow cells (Fig. 2). *Phragmites* has been used in subsurface-flow wetlands, but recently *Baumea articulata*, *Carex fascicularis*, *Phylidrum languinosum* and *Schoenoplectus mucronata* were trialled (Browning and Greenway, 2003).

Between 1992 and 1994, nine experimental pilot wetlands were constructed in northern Queensland to treat secondary effluent. Each wetland had a different configuration and received different-quality effluent (Greenway and Woolley, 1999; QDNR, 2000). In 1995, two large-scale wetlands (Cooroy and Rosewood) were constructed in south-east Queensland (Greenway et al., 2002). Cooroy consists of a lagoon and a series of shallow, densely vegetated marshes and small deep-water 'ponds' (Fig. 1), and treats secondary effluent. Rosewood consists of a lagoon, two surface-flow wetlands and a subsurface-flow wetland (Fig. 2), and treats primary settled effluent.

4.1. Effluent treatment—nutrient removal

The performance of seven surface-flow wetlands is given in Table 1. Performance efficiency varied between wetlands, with good removal of nitrogen but poor removal of phosphorus. Removal efficiency was highest for oxidised nitrogen (ranging from 70 to 98%). At Townsville and Emu Park, nitrate concentrations were reduced from 15.8 mg L⁻¹ and 14.5 mg L⁻¹ to 0.3 mg L⁻¹ and 0.85 mg L⁻¹, respectively, as the

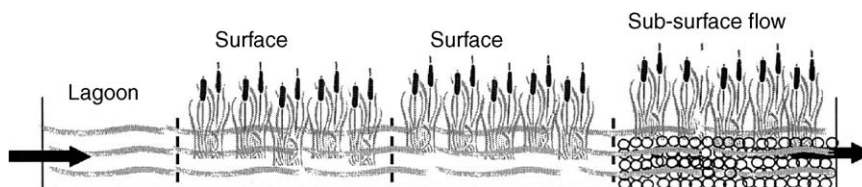


Fig. 2. Combined system of lagoon, surface and subsurface-flow wetland cells (Rosewood, Ipswich City Council).

Table 1
Sewage-effluent nutrient concentrations (mg L^{-1}) into and out of seven pilot surface-flow constructed wetlands in Queensland, Australia

Wetland	HRT (days)	HLR ($\text{m}^3 \text{ha}^{-1} \text{d}^{-1}$)	$\text{NH}_4\text{-N}$		$\text{NO}_3\text{-N}$		TN		$\text{PO}_4\text{-P}$		TP	
			In	Out	In	Out	In	Out	In	Out	In	Out
Cairns	10	500	0.3 ^a	0.2	9	0.1	6	1.5	8	7	8	7
Ingham	12	400	8	5.4	10	3	20	10	6	5.4	7	5.4
Townsville	7	NA	11	2	16	0.3	32	7	6	6	7	7
Emu Park	7	20	2 ^a	0.1	14	0.8	NA	NA	6.2	5.5	NA	NA
Blackall	3	740	9	8	3	0.2	17	14	3	3	3	3
Cooroy	20	NA	13	1	8	1	25	6	0.02 ^b	<0.01	0.2 ^b	<0.05
Rosewood	30	NA	NA	3	NA	2	50 ^c	<5	NA	8	12 ^c	9

^a Oxidation ditch pretreatment for nitrification of NH_4 .

^b Alum dosing pretreatment to remove PO_4 .

^c Influent is primary settled sewage.

effluent flowed through the wetlands with a hydraulic retention time of 7 days (Table 1). At Cairns, efficient nitrification in an upstream oxidation ditch resulted in very low ammonium before entering the wetland ($0.5 \text{ mg NH}_4\text{-N L}^{-1}$), which could not be further reduced in concentration. Nitrate concentrations were reduced from 9 mg L^{-1} to $<0.1 \text{ mg L}^{-1}$. Removal efficiency was lowest for phosphorus (less than 30%), with export in some wetlands. A mass balance over 3 years in the Cairns wetland (Table 2) showed a mass reduction of 21% phosphorus and 85% nitrogen, of which plant biomass accounted for 53% $\text{PO}_4\text{-P}$ removal and 50% $\text{NO}_x\text{-N}$ removal, respectively (Greenway and Woolley, 2001). This demonstrates the ability for direct nutrient removal by macrophytes in subtropical climates where there are high growth rates.

The recently released Guidelines for Water Reuse (US EPA, 2004) suggest that reclaimed water from wastewater treatment usually contains enough nutrients for crop irrigation, but indicate that in some highly efficient systems, nitrogen concentrations may be too low to produce satisfactory crop yields. The wetlands at Cairns, Townsville, Emu Park and Cooroy had particularly low nitrogen concentrations (Table 1). However, at those locations, reuse is for environmental purposes only. The guidelines state “excessive phosphorus levels do not appear to pose any problems to crops but can be a problem in runoff to surface waters” (p. 24). Thus, reuse applications will depend on the nutrient quality of the treated effluent. It may not be necessary to promote the removal of nutrients if the primary purpose of effluent reuse is for crop irrigation. Thus, wetland systems

Table 2
Nutrient mass balance (kg) over 3 years at Cairns (surface-flow constructed wetland) (adapted from Greenway and Woolley, 2001)

	Channel 1		Channel 2		Channel 3	
Area (m^2)	352		352		975	
Inflow (L s^{-1})	0.12		0.22		0.56	
HRT (days)	16		10		11	
HLR ($\text{m}^3 \text{ha}^{-1} \text{d}$)	300		500		500	
Nutrient	Removal (kg)	Removal (%)	Removal (kg)	Removal (%)	Removal (kg)	Removal (%)
Total N	92	85	154	87	386	81
$\text{NO}_x\text{-N}$	51	93	77	88	258	93
$\text{NH}_4\text{-N}$	4 ^a	61	8	74	20 ^a	27
Biomass N	44	86% $\text{NO}_x\text{-N}$	42	54% $\text{NO}_x\text{-N}$	105	41% $\text{NO}_x\text{-N}$
Total P	26	26	45	28	92	21
$\text{PO}_4\text{-P}$	23	27	33	28	70	20
Biomass P	15	66% $\text{PO}_4\text{-P}$	15	45% $\text{PO}_4\text{-P}$	37	47% $\text{PO}_4\text{-P}$

^a In years 1 and 3, there was net export of $\text{NH}_4\text{-N}$ from Channels 1 and 3, hence lower percent removal over 3 years.

could be particularly desirable as low-cost technologies for the treatment of primary settled sewage effluent or secondary effluent with high nitrogen and phosphorus, where nutrients are required for crop growth.

4.2. Suitability of macrophyte species for nutrient removal

Sixty-six species of macrophytes (8 free-floating, 8 creepers, 5 submerged, 5 floating-leaved attached and 40 emergent species) have been identified growing in treatment wetlands receiving secondary effluent in Queensland (Greenway, 2003). Many species were found growing in effluent containing up to $20 \text{ mg L}^{-1} \text{ NH}_4\text{-N}$, $16 \text{ mg L}^{-1} \text{ NO}_x\text{-N}$, and $9 \text{ mg L}^{-1} \text{ PO}_4\text{-P}$. The nutrient content for most of these macrophytes was significantly higher than for controls growing in natural wetlands (Greenway, 1997, 2003), demonstrating the ability of these plants to remove nutrients from the wastewater stream. The nutrient content was within the range of values recorded from other tropical and temperate constructed wetlands (Greenway, 1997), but rhizome tissue has less P and N than plants growing in temperate Australia, suggesting the rhizomes are less likely to function as storage organs for nutrients where climatic conditions are conducive to year-round growth. Plant biomass and annual production rates are high in the tropical/subtropical regions (Browning and Greenway, 2003; Greenway and Woolley, 2001) (Table 3). In an experimental mesocosm band planted with *Phragmites*, *Schoenoplectus*

and *Eleocharis*, mean shoot biomass after 12 months growth was 2200 g DW m^{-2} (7 g P; 38 g N) (QDNR, 2000). Regrowth from cropping yielded an annual production rate of 3500 g m^{-2} and 10 g P; 58 g N. These growth rates are comparable to the Cairns study (Greenway and Woolley, 2001), and further indicate the potential of these macrophyte species for nutrient removal. Tanner (2001) reported maximum nutrient accumulations of $8.8\text{--}13.4 \text{ g P m}^{-2}$ and $48\text{--}69 \text{ g N m}^{-2}$ in total biomass (shoots and below ground) of bulrush in New Zealand, but indicated this only accounted for 2–8% TN removal, due to the higher nutrient loading rates compared to the Cairns studies. Tanner concluded that “uptake and storage of N and P in live plant biomass can usually only account for a fraction of the improved performance of planted systems” (p. 12). However, it should be recognised that plants have a maximum removal and storage capacity, and if effluent loading rates are low, then the relative removal efficiency by macrophytes will be higher.

4.3. Effluent treatment—pathogen removal

Studies in Queensland, Australia (Bolton and Greenway, 1999; QDNR, 2000), have shown that constructed wetlands can remove 95% of pathogen and indicator organisms. A summary of available information on faecal-coliform removal in constructed wetlands in Queensland is given in Table 4. The removal of these faecal indicator bacteria also suggests the removal of pathogenic microorganisms. Despite high removal

Table 3

Plant-shoot biomass and production in a tropical surface-flow wetland (a) and a subtropical subsurface-flow wetland (b)

Species	Biomass (g m^{-2})			Annual production ($\text{g m}^{-2} \text{ y}^{-1}$)		
	DW	P	N	DW	P	N
(a) Plant-shoot biomass and production in a tropical surface-flow wetland						
<i>Typha domingensis</i>	1750	6.6	23.6	4000	15.2	54.0
<i>Eleocharis sphacelata</i>	1000	4.2	15	3000	12.6	40.5
<i>Schoenoplectus validus</i>	800	2.8	11.6	1000	3.5	14.5
<i>Marsilia</i> sp.	370	3.6	10			
Duckweed (<i>Spirodela</i>)	40	0.58	1.7	2000	28.8	86.0
<i>Ceratophyllum demersum</i>	90	1.7	3.2			
(b) Plant-shoot biomass and production in a subtropical subsurface-flow wetland						
<i>Baumea articulata</i>	2160	5.6	34	3400	9.0	55
<i>Carex fascicularis</i>	2000	4.6	30.3	4000	9.2	60.6
<i>Schoenoplectus mucronatus</i>	615	2.0	9.2	1000	3.3	14.5

Source: (a) Greenway and Woolley (2001) and (b) Browning and Greenway (2003).

Table 4
Faecal-coliform removal from three surface-flow wetlands and two subsurface-flow wetlands in Queensland

Location	Cairns ^a		Townsville ^a	Blackall ^a	Oxley	Logan ^b
Wetland type	Surface		Surface	Surface	Subsurface	Melaleuca
Effluent	Secondary		Secondary	Secondary	Secondary	Primary
HRT (days)	16	11	7–10	7	4–5	2
Influent (cfu/100 mL)	79500	79500	84000	36000	1600	1×10^7
Effluent (cfu/100 mL)	1100	2900	300–700	110–195	300–900	<1000
Removal (%)	98.7	96.4	99.6	99.6	82	99.9

^a QDNR (2000).

^b Bolton and Greenway (1999).

efficiencies, faecal-coliform concentrations in the final effluent are often still between 100 cfu/100 mL and 1000 cfu/100 mL. These concentrations are within the range of background concentrations found in many natural wetlands (IWA, 2000), and are acceptable for a range of reuse applications including irrigation of crops and golf courses.

5. Constructed-wetland effluent reuse in Queensland

All Queensland local governments are under considerable pressure to comply with new environmental-protection legislation, and the disposal of secondary-treated effluent into coastal and inland waters is being discouraged. In addition, the use of chlorine as a disinfectant has been discouraged. Effluent discharging into the waters of the Great Barrier Reef Marine Park, which extends for 2000 km along the Queensland Coast, is of particular concern because of the sensitivity of the marine ecosystems to nutrient enrichment and increased turbidity. Thus, effluent reuse, including land disposal for irrigation, is high on the agenda. Examples of effluent reuse from the wetlands at Ingham, Townsville and Blackall are given below. All three wetlands reduced nitrogen to acceptable concentrations for irrigation (Table 1), and considerable reduction in faecal coliforms occurred at Townsville and Blackall (Table 4).

The objective of the Ingham Wetland (situated in tropical north Queensland) is to polish wastewater effluent to an acceptable standard for creek discharge and to eliminate chlorine as a disinfection process. In addition, effluent reuse includes: pumping the effluent to a 10 ha joint wetland adjacent to the sugar mill, scrub-

bing flue gases in the sugar mill and irrigating farms in the area. The wetland reduced nitrogen to 10 mg L^{-1} which is acceptable for irrigation (Table 1). No data are available for Ingham on faecal coliforms.

The objective of the Townsville Wetland (situated in the dry tropics) is to polish the effluent from the wastewater-treatment plant and then discharge to the adjacent Town Common, to mitigate the drought situation and restore the natural wetland environment and wildlife populations. The Town Common is a popular tourist spot for bird watching, and permanent water ensures year-round bird life and hence visitors. The constructed wetland was highly effective in reducing ammonium and nitrate to 2 mg L^{-1} and 0.03 mg L^{-1} , respectively (Table 1). Such low concentrations are acceptable for discharge into a natural wetland. Discharge onto the Town Common has been highly effective in achieving its reuse objective. It has promoted lush growth of aquatic and wetland vegetation which has encouraged flocks of magpie geese, broilgas, and a wide variety of water fowl and wading birds to visit the Common during the drought and dry seasons.

The objective of the Blackall Wetland (situated in the arid western region) is to reuse the wastewater effluent for the town's open spaces. Nutrient retention is considered more important than removal, but pathogen removal is necessary to protect public health. The higher HLR, shorter HRT (3 days), and absence of dense vegetation in the Blackall Wetland (Table 1) may have been reasons for poor nutrient removal. However, the open water probably facilitated the high reductions in faecal coliforms (Table 4). Effluent reuse schemes include: irrigating commercial tree-lots of different species of flowering gums for export; developing a riverbank ecotourism wetland complex, using native plants and trees typical of western Queensland,

irrigated with effluent; maintaining water levels in the natural billabong, as well as the duck pond; irrigating community golf courses, parks and gardens in order to conserve the dwindling resources of the Great Artesian Basin.

6. Wetland design for enhanced effluent treatment in Queensland

In subtropical, tropical and arid Queensland, surface-flow wetlands offer great potential for polishing wastewater effluent to a standard suitable for reuse. In order to maximise nutrient removal, a combination of macrophyte types should be used, including free-floating (e.g. duckweed) and submerged species (e.g. *Ceratophyllum* and *Potamogeton*), to remove nutrients directly from the water column; rooted species, to remove nutrients from the sediment and aerate the rhizosphere zone for nitrification. A large surface area should be provided for biofilm/periphyton attachment by the submerged stems of emergent plants, water lilies and submerged plants. These periphyton communities will also remove nutrients from the water column. Open-water areas can promote phytoplankton uptake of nutrients.

In order to maximise pathogen removal, a combination of densely vegetated and open-water zones should be used. The densely vegetated zones will maximise filtration and sedimentation of particles to which pathogens will be adsorbed, while the open-water zones will maximise UV disinfection. Healthy populations of natural-wetland microbes (bacteria and viruses) should be encouraged to promote predation, lysis and competition with pathogenic human microbes. Extended detention times greater than 5 days are also recommended for enhanced pathogen removal. A final subsurface filtration through gravel or sand is also recommended. Thus, a combined system as shown in Fig. 2 would maximise both nutrient and pathogen removal.

With respect to minimising mosquito breeding, wetland design should include both shallow marsh and deep open-water ponds with a diversity of plant species and at least 30% open water. Aggressive species which form monospecific stands or die off in winter to produce a thick interwoven mat of stems, e.g. *Typha*, should be avoided. Species that produce dense floating rafts, e.g.

Paspalum grass and other aquatic creepers, should also be avoided. As a management task, excessive dense mats of dead or creeping aquatic vegetation should regularly be removed.

7. Conclusions

Currently, nearly all Queensland local governments are under considerable pressure to comply with environmental legislation on water-quality discharge. These factors and the extended drought have highlighted the need to polish effluent to a higher standard suitable for discharge or for irrigation and other forms of reuse. Constructed-wetland technology presents itself as a viable option for reducing nutrients and performing the function of disinfection. Since constructed wetlands provide a low-cost alternative to tertiary Biological Nutrient Removal, this may be more appealing for small communities where the cost of upgrading treatment works can be prohibitive. The treated wastewater from these wetlands (a scarce resource during the dry season and in arid regions) can be used to irrigate crops, playing fields, parks and gardens, or golf courses. The water discharged from constructed wetlands can be an acceptable quality to flow into estuarine and riverine environments. Many natural wetlands are only seasonally inundated, and during the dry season wildlife has to seek alternative refuges. Constructed wetlands can provide alternative habitats or the treated effluent can be used to restore natural wetlands.

The use of secondary-treated, or even tertiary effluent, for irrigation is regarded as a health risk if it has not been disinfected to remove potential human pathogenic microorganisms, and disinfection comes at a cost. Constructed wetlands can be designed to maximise pathogen removal by incorporating lagoons, surface-flow wetlands and subsurface-flow wetlands into a treatment train. Constructed wetlands are also multifunctional ecological systems and can assist in restoring our aquatic flora and fauna.

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